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Simplified Space Vector PWM Algorithm for a Three Level Inverter

K Abhishekam
M.Tech Student of Electrical Engineering
RGMCET, Nandyal-518501
Email: abhishekam39@gmail.com

K Sri Gowri
Professor of Electrical Engineering
RGMCET, Nandyal-518501
Email: gowrivasu.3@gmail.com

Abstract**—**The Space vector based PWM strategies have broader choice of switching sequences to generate the required reference vector than triangle comparison based PWM techniques for three-level inverters. However, Space Vector based PWM technique involves various steps which are computationally exhaustive. In order to reduce this complexity, a simplified algorithm is proposed here. This work aims at reducing of harmonic distortion in high-power drives, which have low switching frequencies. In this paper, Conventional Space Vector based PWM (CSVPWM) algorithm and Modified Space Vector based PWM (MSVPWM) algorithm are presented.

Index Terms**—**multilevel inverter, computational efforts, Conventional Space Vector based PWM, Modified Space Vector based PWM

INTRODUCTION

The multilevel converters role increased in industry and academia as one of the preferred choices of power conversion for high power applications. Multilevel inverters produce output waveform of better quality than two level inverters for the same device switching frequency. Three-level neutral point clamped (NPC) inverters can switch higher DC bus voltages than two level inverters with same device voltage ratings. [1]-[4]. The power circuit of three-level NPC inverter is shown in Fig.1. The *pole voltage,* v_{RO} defined as, the voltage at midpoint of leg with respect to voltage at midpoint of DC bus, and it related to the status of switches. The switch status, state and pole voltages are shown in Table I.

In high- power applications, the output voltage waveform of voltage source inverter must synchronized with its own fundamental component. The quality of output waveform of an inverter depends on PWM technique is used. There are two types of PWM generation that are triangle comparison based PWM generation and space vector based PWM (SVPWM) generation [5]. In these two, SVPWM has greater flexibility in terms of switching sequence in which proper switching states are applied to generate the given reference vector. Such switching sequences involve application of an inverter state double switching of a phase in a subcycle and have been shown to reduce the harmonic distortion at high modulation

indices, [4],[5]. By using proper switching states, it is possible to get synchronization and symmetry in SVPWM algorithm.

In order to reduce the switching losses multilevel inverters are generally used in high-power applications where the switching frequency is less than 1 kHz [1]. At low switching frequencies, the *pulse number* P, defined as the ratio of switching frequency to the fundamental frequency is low. To make sure that the waveform quality is good under such conditions, all the waveform symmetries and synchronization has to be maintained [2], [3], [5]. In case of synchronized PWM, pulse number should be an integer. Three phase symmetry (TPS) and half wave symmetry (HWS) require further restriction on P. in case of synchronized CSVPWM, the pulse number belongs to series 2,5,8,11,…..if these symmetries are to be preserved [2], [3]. Conversely, by exploiting the flexibilities in terms of switching sequences offered by SVPWM, MSVPWM approach relaxes this restriction on P considerably. This approach can produce PWM waveforms of any integral pulse number, P, maintaining all the waveform symmetries [2], [3].

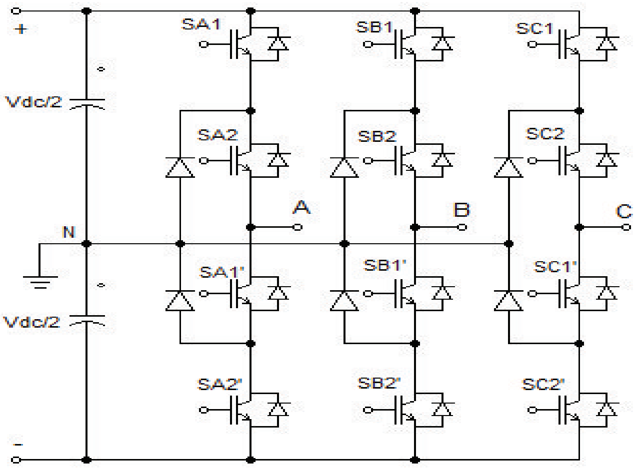

Fig.1. Neutral point clamped (NPC) three level inverter

TABLE I
SWITCH STATUS, STATE AND POLE VOLTAGE

Switch status	State	Pole voltage, v_{RO}
SR1=ON, SR2=ON	+	Vdc/2
SR1=OFF, SR2=ON	0	0
SR1=OFF, SR2=OFF	-	-Vdc/2

However SVPWM strategies have their advantages in terms of switching sequences, their implementation is computationally
have a number of mathematical steps are involved [2], [3]. These require more computational efforts. The main objective of this paper is to reduce the computational complexity in SVPWM strategies. The simplified algorithm is reduces computational efforts. The steps involved in simplified algorithm are explained in section III. CSVPWM, MSVPWM algorithms are explained. Simulation results are presented in section IV.

EXISTING ALGORITHM FOR **SVPWM**

The space vector diagram for three-level NPC inverter is shown in Fig. 2. There are six vectors each of magnitude V_{dc} and six vectors each of magnitude $0.866V_{dc}$ and six vectors each of magnitude $0.5V_{dc}$ and a zero vector.

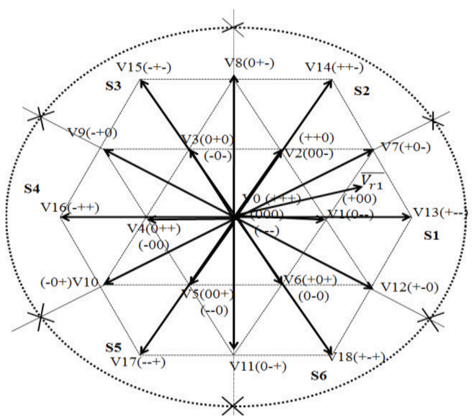

Fig. 2. Space vectors of a three-level inverter with sector identification

Here the reference vector $\overline{Vr}$ is obtained by time averaging of three nearest vectors $\overline{Va}$, $\overline{Vb}$, $\overline{Vc}$ in a subcycle as shown below:

$$\overline{Va}Ts = \overline{Va}Tx + \overline{Vb}Ty + \overline{Vc}Tz \qquad (1)$$

$$T_s = T_x + T_y + T_z$$

Here T_x, T_y and T_z are the dwell times of $\overline{Va}$, $\overline{Vb}$ and $\overline{Vc}$, respectively.

To maintain volt-second balance the three nearest vectors of reference vector are to be identified and their dwell times are to be calculated.

The magnitudes of $0.5V_{dc}$ vectors sometimes referred as *pivot vectors*. Identify the nearest pivot vector of reference vector $\overline{Vr}$ and subtracted pivot vector from the reference vector $\overline{Vr}$. Then the required reference vector $\overline{Vr'}$ is obtained.

The conceptual two-level inverter is shown in Fig. 3. Here to synthesize the given reference vector, two active vectors and two null or zero vectors are used. The dwell times are calculated as in the case of two-level inverter and this involves trigonometric

functions and requires look-up tables, significant computation effort [2] – [4].

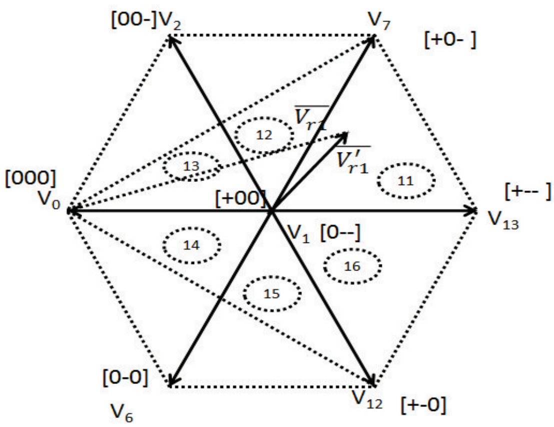

Fig. 3. Space vector diagram of an equivalent two level inverter

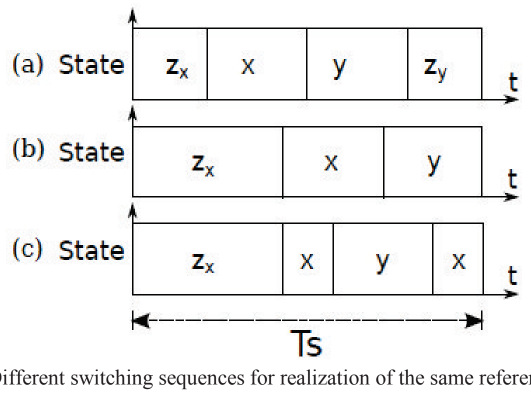

Fig. 4. Different switching sequences for realization of the same reference vector

The active vectors $\overline{Va}$ and $\overline{Vb}$ correspond to the inverter states x and y respectively. The pivot vector $\overline{Vc}$ (zero or null vector) is produced two states, that are z_x and z_y. The three nearest vectors of required reference vector states can be applied for different sequences as shown in Fig. 4. To get the required reference vector two active states (x and y) and two zero states (z_x and z_y) are applied. The first sequence is for CSVPWM and all the three are for MSVPWM. In this paper second sequence is used for the MSVPWM. Such types of more sequences are discussed in [4].

In synchronized PWM schemes, the number of samples per sector (N) must be an integer, because of the reference vector is sampled at integer multiple of six times the fundamental frequency. This achieves synchronization, HWS, TPS conditions [2], [3]. Moreover, the samples are placed symmetrically within the sector. This achieves the quarter wave symmetry (QWS) conditions [2], [3].

The sequence for every sample in the CSVPWM strategy is must start with one of the zero states and ends

TABLE II
SEQUENCES FOR CSVPWM AND MSVPWM

Sample	CSVPWM	MSVPWM	
	N = Odd	N = Odd	N = Even
1^{st}	$z_y \rightarrow y \rightarrow x \rightarrow z_x$	$z_y \rightarrow y \rightarrow x \rightarrow z_x$	$x \rightarrow y \rightarrow x \rightarrow z_x$
2^{nd} to $(N\text{-}1)^{th}$	$z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$	$z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$	$z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$
N^{th}	$z_y \rightarrow y \rightarrow x \rightarrow z_x$	$z_y \rightarrow y \rightarrow x$	$z_x \rightarrow x \rightarrow y \rightarrow x$
Pulse Number (P)	$\frac{3N+1}{2}$	$\frac{3N-1}{2}$	$\frac{3N}{2}$

with other. The final state of the present sample must be initial state for the next sample. The number of samples per sector must be odd in CSVPWM, and sequence is always followed as $z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$. Thus there are three switching transitions in every subcycle. Through the sector change over, the zero state z_x, of the old sector, is the state x, for the next sector. This includes additional switching during sector change over [2], [3]. In CSVPWM the pulse number is given by $P = \frac{3N+1}{2}$, or P follows the series 2,5,8,11….[2], [3].

In MSVPWM, the number of samples per sector can be odd or even. If the N is odd, then the pulse number is given by $P = \frac{3N-1}{2}$ and if the N is even, then the pulse number is given by $P = \frac{3N}{2}$. In MSVPWM the switching sequence used for the last sample is modified as indicated in Table II.

The extra switching involved is therefore avoided [3] in the MSVPWM. From the table, P can take any integral value. Based on pulse number, the number samples per sector, N can be calculated from the equations as given in Table II. For the particular sample the sequences applied for CSVPWM and MSVPWM as shown in Table II. The sequence for the N^{th} sample is modified in MSVPWM as $z_y \rightarrow y \rightarrow x$ [6].

The frame has been given here to simplify the steps involved and reduce the computation effort as discussed in the following section.

SIMPLIFIED ALGORITHM FOR SVPWM

Instead of reference vector, $\overline{Vr}$, the three-phase sinusoidal signals, (m_a, m_b and m_c) are used in this simplified algorithm. At any instant of sample, these three-phase signals represents the reference vector. Here m_a, m_b and m_c are the modulating waves or signals.

In this simplified algorithm, the sector in which reference vector, $\overline{Vr}$ is present identified based on modulating signals m_a, m_b and m_c as shown in Table III, whereas, in SVPWM, the sector is identified based on its angle.

TABLE III
INDETIFICATION OF SECTOR

Condition	Sector
$\lvert m_a\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_a>0$	1
$\lvert m_a\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_a<0$	4
$\lvert m_b\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_b>0$	3
$\lvert m_b\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_b<0$	6
$\lvert m_c\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_c>0$	5
$\lvert m_c\rvert = max(\lvert m_a\rvert, \lvert m_b\rvert, \lvert m_c\rvert);\ m_c<0$	2

Once the sector is identified, reference vector is shifted to the first sector by equation (2). This equation involves computational complexity.

$$\overline{Vr1} = Vref\ e^{j*(Sector-1)\pi/3} \qquad (2)$$

To avoid this complexity, another method is, rotating the modulating signals is carried out as indicated in Table IV. Here all sectors modulating signals shifted to the first sector. This involves very little computational efforts.

Here M_a, M_b and M_c are the shifted modulating signals, and represent shifted reference vector $\overline{Vr1}$.

TABLE IV
SHIFTING THE MODULATING SIGNALS TO FIRST SECTOR

Sector	***Ma***	***Mb***	***Mc***
1	***ma***	***mb***	***mc***
2	***-1*mc***	***-1*ma***	***-1*mb***
3	***mb***	***mc***	***ma***
4	***-1*ma***	***-1*mb***	***-1*mc***
5	***mc***	***ma***	***mb***
6	***-1*mb***	***-1*mc***	***-1*ma***

In the conceptual two-level inverter, the equivalent reference vector $\overline{Vr'}$ can obtain by subtracting the pivot vector of the first sector V_1 from $\overline{Vr1}$.(from fig. 3.)

The required reference vector is obtained by using Eqn. (3). Here, the pivot vector is subtracted from M_a, M_b and M_c using Eqn. (3)

$$\begin{gathered} Ma' = Ma - \frac{V_{dc}}{3}; \\ Mb' = Mb - \frac{-V_{dc}}{6}; \\ Mc' = Mc - \frac{-V_{dc}}{6}; \end{gathered} \qquad (3)$$

The subsector is identified in the conceptual two-level inverter, based on the angle of equivalent reference vector, $\overline{Vr'}$. In the proposed algorithm, the subsector is identified based on M_a', M_b' and M_c' as indicated in Table V.

TABLE V
IDENTIFICATION OF SUBSECTOR

Condition 1	**Condition 2**	**Subsector**
$M_a' \geq 0$ and $(M_b' - M_c') \geq 0$	***$(M_b' - M_c') \geq 3*M_a'$***	***2***
	$(M_b' - M_c') < 3*M_a'$	***1***
$M_a' \leq 0$ and $(M_b' - M_c') \leq 0$	***$(M_b' - M_c') \geq 3*M_a'$***	***4***
	$(M_b' - M_c') < 3*M_a'$	***5***
$M_a' \geq 0$ and $(M_b' - M_c') \leq 0$	***$(M_c' - M_b') \geq 3*M_a'$***	***5***
	$(M_c' - M_b') < 3*M_a'$	***6***
$M_a' \leq 0$ and $(M_b' - M_c') \geq 0$	***$(M_c' - M_b') \leq 3*M_a'$***	***2***
	$(M_c' - M_b') > 3*M_a'$	***3***

In the conceptual two-level inverter, the dwell time is computed using equivalent reference vector $\overline{Vr'}$. It requires more trigonometric functions consuming significant computation time.

In the proposed algorithm, the modulating signals (M_a', M_b' and M_c'), are readily available, the dwell times are computed by simple difference between them.

The dwell times of the active states (*x,y*) are obtained by Eqn. (4).

$$T_x = 2 * (M_b' - M_a') * T_s$$
$$T_y = 2 * (M_a' - M_c') * T_s \quad (4)$$

The dwell times of the states for various subsectors obtained by using modulating signals M_a', M_b' and M_c'as given in TableVI.

Based on the above steps, the sector and subsector are identified, and the dwell times are computed. Now choose the proper switching states and they can be outputted such that required reference vector is produced.

TABLE VI
DWELL TIME COMPUTATION IN EACH OF SUBSECTOR

Subsector	Time-x	Time-y	Time-z
1	*2(Ma'- Mb')Ts*	*2(Mb'- Mc')Ts*	*Ts-Tx-Ty*
2	*2(Ma'- Mc')Ts*	*2(Mb'- Ma')Ts*	*Ts-Tx-Ty*
3	*2(Mb'- Mc')Ts*	*2(Mc'- Ma')Ts*	*Ts-Tx-Ty*
4	*2(Mb'- Ma')Ts*	*2(Mc'- Mb')Ts*	*Ts-Tx-Ty*
5	*2(Mc'- Ma')Ts*	*2(Ma'- Mb')Ts*	*Ts-Tx-Ty*
6	*2(Mc'- Mb')Ts*	*2(Ma'- Mc')Ts*	*Ts-Tx-Ty*

CONCLUSIONS

The space vector based PWM strategies have the advantage of different possible switching sequences for a given reference vector. Moreover, different switching sequences can be used in different subcycles. A simplified algorithm of space vector based PWM strategies for three-level inverter is proposed here.

The proposed algorithm maintains synchronization, QWS, HWS, and TPS for all integer values of P. This is achieved with the usual approach without any computational requirements. This algorithm reduces the computational efforts required for space vector based PWM strategies.

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BIOGRAPHIES

K.Abhishekam is born in 1989 in India. He has graduated from Rajeev Gandhi Memorial College Of engineering and Technology, Nandyal in 2011. Presently he is pursuing post graduation in Power electronics Specialization at RGM College of engineering and Technology, Nandyal. His areas of interested include Power electronics, Drives and Control and Pulse Width Modulation Techniques.
E.Mail: abhishekam39@gmail.com

Dr. K.Sri Gowri received the B.Tech degree from SVU college of Engineering, Tirupati in1997, the M.Tech degree from RGM College of Engineering and Technology, Nandyal and has been awarded Ph.D in the area of Power Electronic Control of Electric Drives from JNTU Kakinada in 2010. She is currently Professor in the Department of EEE in RGMCET, Nandyal, A.P. Her areas of interest include Power Electronics, Pulse Width Modulation Techniques, Drives and Control and Renewable Sources of Energy.
E-mail: gowrivasu.3@gmail.com